Heavy Ion Collisions at Relativistic Energies: Testing a Nuclear Matter at High Baryon and Isospin Density

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We show that the phenomenology of isospin effects on heavy ion reactions at intermediate energies (few $AGeV$ range) is extremely rich and can allow a "direct" study of the covariant structure of the isovector interaction in the hadron medium. We work within a relativistic transport frame, beyond a cascade picture, consistently derived from effective Lagrangians, where isospin effects are accounted for in the mean field and collision terms. Rather sensitive observables are proposed from collective flows ("differential" flows) and from pion/kaon production (π^-/π^+, K^0/K^+ yields). For the latter point relevant non-equilibrium effects are stressed. The possibility of the transition to a mixed hadron-quark phase, at high baryon and isospin density, is finally suggested. Some signatures could come from an expected "neutron trapping" effect.

1. Introduction

Recently the development of new heavy ion facilities (radioactive beams) has driven the interest on the dynamical behaviour of asymmetric matter, see the recent reviews [1, 2]. Here we focus our attention on relativistic heavy ion collisions, that provide a unique terrestrial opportunity to probe the in-medium nuclear interaction in high density and high momentum regions. An effective Lagrangian approach to the hadron interacting system is extended to the isospin degree of freedom: within the same frame equilibrium properties (EoS, [3]) and transport dynamics [4, 5] can be consistently derived.

Within a covariant picture of the nuclear mean field, for the description of the symmetry energy at saturation (a_4 parameter of the Weizsäecker mass formula) (a) only the Lorentz vector ρ mesonic field, and (b) both, the vector ρ (repulsive) and scalar δ (attractive) effective fields [6, 7] can be included. In the latter case the competition between scalar and vector fields leads to a stiffer symmetry term at high density [6, 2]. We present here observable effects, in fact enhanced, in the dynamics of heavy ion collisions. Here we focus our attention on collective isospin flows, in particular the elliptic ones, and on the isospin content of particle production, in particular kaons. We finally show that in the compression stage of isospin asymmetric collisions we can enter a mixed deconfined phase, if the EoS conditions for the existence of quark stars are met.

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2. Relativistic Transport

The starting point is a simple phenomenological version of the Non-Linear (with respect to the iso-scalar, Lorentz scalar σ field) Walecka effective theory which corresponds to the Hartree or Relativistic Mean Field (RMF) approximation within the Quantum-Hadro-Dynamics [3]. According to this model the presence of the hadronic medium leads to effective masses and momenta $M^* = M + \Sigma_s$, $k^{*\mu} = k^\mu - \Sigma^\mu$, with Σ_s, Σ^μ scalar and vector self-energies. For asymmetric matter the self-energies are different for protons and neutrons, depending on the isovector meson contributions. We will call the corresponding models as $NL\rho$ and $NL\rho\delta$, respectively, and just NL the case without isovector interactions. For the more general $NL\rho\delta$ case the self-energies of protons and neutrons read:

$$\Sigma_s(p,n) = -f_\sigma \sigma(\rho_s) \pm f_\delta \rho_{s3}, \quad \Sigma^\mu(p,n) = f_\omega j^\mu \mp f_\rho j_3^\mu, \quad (upper\ signs\ for\ neutrons), (1)$$

where $\rho_s = \rho_{sp} + \rho_{sn}$, $j^\alpha = j_p^\alpha + j_n^\alpha$, $\rho_{s3} = \rho_{sp} - \rho_{sn}$, $j_3^\alpha = j_p^\alpha - j_n^\alpha$ are the total and isospin scalar densities and currents and $f_{\sigma,\omega,\rho,\delta}$ are the coupling constants of the various mesonic fields. $\sigma(\rho_s)$ is the solution of the non linear equation for the σ field [6, 2].

For the description of heavy ion collisions we solve the covariant transport equation of the Boltzmann type [4, 5] within the Relativistic Landau Vlasov (RLV) method, using phase-space Gaussian test particles [8], and applying a Monte-Carlo procedure for the hard hadron collisions. The collision term includes elastic and inelastic processes involving the production/absorption of the $\Delta(1232MeV)$ and $N^*(1440MeV)$ resonances as well as their decays into pion channels, [9].

It is worth to note that the nucleon mean field (Vlasov) propagation is given by the following equations of motion for the test particles trajectories [2]:

$$\frac{d}{d\tau}x_i^\mu = \frac{p_i^*(\tau)}{M_i^*(x)}, \qquad \frac{d}{d\tau}p_i^{*\mu} = \frac{p_{i\nu}^*(\tau)}{M_i^*(x)}F_i^{\mu\nu}(x_i(\tau)) + \partial^\mu M_i^*(x). \qquad (2)$$

In order to have an idea of the dynamical effects of the covariant nature of the interacting fields, we write down, with some approximations, the "force" acting on a particle. Since we are interested in isospin contributions we will take into account only the isovector part of the interaction [10]:

$$\frac{d\vec{p}_i^*}{d\tau} = \pm f_\rho \frac{p_{i\nu}}{M_i^*}\left[\vec{\nabla}J_3^\nu - \partial^\nu \vec{J}_3\right] \mp f_\delta \nabla \rho_{S3} \approx \pm f_\rho \frac{E_i^*}{M_i^*}\vec{\nabla}\rho_3 \mp f_\delta \vec{\nabla}\rho_{S3}, \quad (upper\ signs\ proton) (3)$$

The Lorentz force (first term of Eq.(3)) shows a $\gamma = \frac{E_i^*}{M_i^*}$ boosting of the vector coupling, while from the second term we expect a γ-quenched δ contribution.

3. Collective Flows

The flow observables can be seen respectively as the first and second coefficients of a Fourier expansion of the azimuthal distribution [11]: $\frac{dN}{d\phi}(y,p_t) \approx 1 + 2V_1 cos(\phi) + 2V_2 cos(2\phi)$ where $p_t = \sqrt{p_x^2 + p_y^2}$ is the transverse momentum and y the rapidity along beam direction. The transverse flow can be expressed as: $V_1(y,p_t) = \langle \frac{p_x}{p_t} \rangle$. The sideward
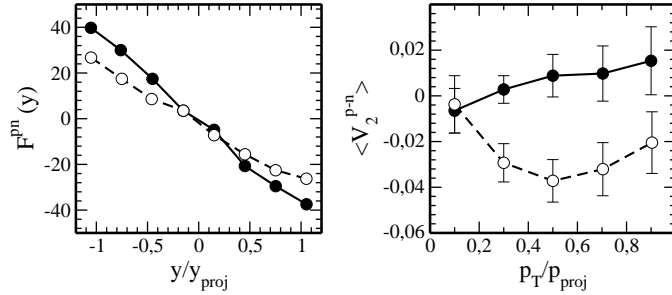
Figure 1. Differential neutron-proton flows for the $^{132}Sn +^{124} Sn$ reaction at 1.5 $AGeV$ ($b = 6fm$) from the two different models for the isovector mean fields. Left: Transverse Flows. Right: Elliptic Flows. Full circles and solid line: $NL\rho\delta$. Open circles and dashed line: $NL\rho$.

(transverse) flow is a deflection of forwards and backwards moving particles, within the reaction plane. The second coefficient of the expansion defines the elliptic flow given by $V_2(y, p_t) = \langle \frac{p_x^2 - p_y^2}{p_t^2} \rangle$. It measures the competition between in-plane and out-of-plane emissions. The sign of V_2 indicates the azimuthal anisotropy of emission: particles can be preferentially emitted either in the reaction plane ($V_2 > 0$) or out-of-plane ($squeeze - out$, $V_2 < 0$) [11, 12]. For the isospin effects the neutron-proton $differential$ flows $V_{1,2}^{(n-p)}(y, p_t) \equiv V_{1,2}^n(y, p_t) - V_{1,2}^p(y, p_t)$ have been suggested as very useful probes of the isovector part of the EoS since they appear rather insensitive to the isoscalar potential and to the in medium nuclear cross sections, [13].

In heavy-ion collisions around $1AGeV$ with radioactive beams, differential flows will directly exploit the Lorentz nature of a scalar and a vector field, see the different γ-boosting in the local force, Eq.(3). In Fig.1 transverse and elliptic differential flows are shown for the $^{132}Sn +^{124} Sn$ reaction at 1.5 $AGeV$ ($b = 6fm$), [10]. The effect of the different structure of the isovector channel is clear. Particularly evident is the splitting in the high p_t region of the elliptic flow. In the ($\rho + \delta$) dynamics the high-p_t neutrons show a much larger $squeeze - out$. This is fully consistent with an early emission (more spectator shadowing) due to the larger ρ-field in the compression stage. We expect similar effects, even enhanced, from the measurements of differential flows for light isobars, like ^3H $vs.$ ^3He.

4. Isospin effects on sub-threshold kaon production at intermediate energies

Kaon production has been proven to be a reliable observable for the high density EoS in the isoscalar sector [14, 15, 16] Here we show that the $K^{0,+}$ production (in particular the K^0/K^+ yield ratio) can be also used to probe the isovector part of the EoS.

Using our RMF transport approach we analyze pion and kaon production in central $^{197}Au +^{197} Au$ collisions in the $0.8 - 1.8$ $AGeV$ beam energy range, comparing models giving the same "soft" EoS for symmetric matter and with different effective field choices for E_{sym}. We will use three Lagrangians with constant nucleon-meson couplings ($NL...$ type, see before) and one with density dependent couplings (DDF, see [7]), recently suggested for better nucleonic properties of neutron stars [17]. In the DDF model the f_ρ is exponentially decreasing with density, resulting in a rather "soft" symmetry term at high density. The hadron mean field propagation, which goes beyond the "collision cascade"
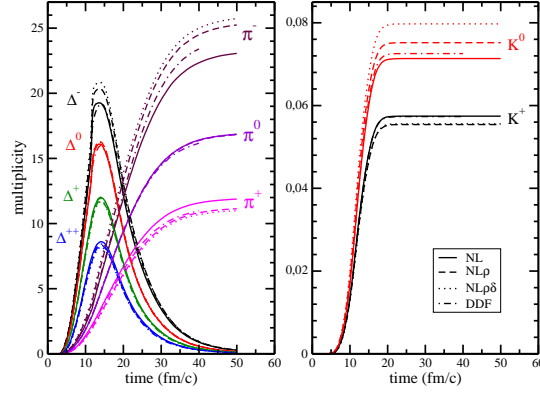
Figure 2. Time evolution of the $\Delta^{\pm,0,++}$ resonances and pions $\pi^{\pm,0}$ (left), and kaons ($K^{+,0}$ (right) for a central ($b = 0$ fm impact parameter) Au+Au collision at 1 AGeV incident energy. Transport calculation using the $NL, NL\rho, NL\rho\delta$ and DDF models for the iso-vector part of the nuclear EoS are shown.

picture, is essential for particle production yields: in particular the isospin dependence of the self-energies directly affects the energy balance of the inelastic channels.

Fig. 2 reports the temporal evolution of $\Delta^{\pm,0,++}$ resonances, pions ($\pi^{\pm,0}$) and kaons ($K^{+,0}$) for central Au+Au collisions at $1 AGeV$. It is clear that, while the pion yield freezes out at times of the order of $50 fm/c$, i.e. at the final stage of the reaction (and at low densities), kaon production occur within the very early (compression) stage, and the yield saturates at around $20 fm/c$. From Fig. 2 we see that the pion results are weakly dependent on the isospin part of the nuclear mean field. However, a slight increase (decrease) in the π^- (π^+) multiplicity is observed when going from the NL (or DDF) to the $NL\rho$ and then to the $NL\rho\delta$ model, i.e. increasing the vector contribution f_ρ in the isovector channel. This trend is more pronounced for kaons, see the right panel, due to the high density selection of the source and the proximity to the production threshold.

When isovector fields are included the symmetry potential energy in neutron-rich matter is repulsive for neutrons and attractive for protons. In a HIC this leads to a fast, pre-equilibrium, emission of neutrons. Such a *mean field* mechanism, often referred to as isospin fractionation [1, 2], is responsible for a reduction of the neutron to proton ratio during the high density phase, with direct consequences on particle production in inelastic NN collisions.

Threshold effects represent a more subtle point. The energy conservation in a hadron collision in general has to be formulated in terms of the canonical momenta, i.e. for a reaction $1+2 \rightarrow 3+4$ as $s_{in} = (k_1^\mu + k_2^\mu)^2 = (k_3^\mu + k_4^\mu)^2 = s_{out}$. Since hadrons are propagating with effective (kinetic) momenta and masses, an equivalent relation should be formulated starting from the effective in-medium quantities $k^{*\mu} = k^\mu - \Sigma^\mu$ and $m^* = m + \Sigma_s$, where Σ_s and Σ^μ are the scalar and vector self-energies, Eqs.(1). The self-energy contributions will influence the particle production at the level of thresholds as well as of the phase space available in the final channel

In neutron-rich colliding systems *Mean field* and *threshold* effects are acting in opposite directions on particle production and might compensate each other. As an example, nn collisions excite $\Delta^{-,0}$ resonances which decay mainly to π^-. In a neutron-rich matter the mean field effect pushes out neutrons making the matter more symmetric and thus decreasing the π^- yield. The threshold effect on the other hand is increasing the rate of
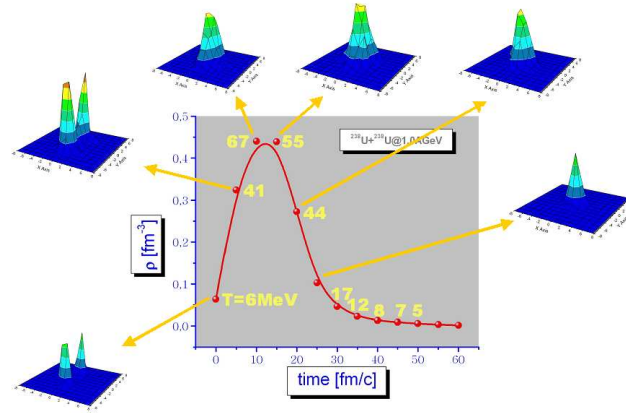
Figure 3. $^{238}U +^{238} U$, 1 $AGeV$, semicentral. Correlation between density, temperature, momentum thermalization inside a cubic cell, 2.5 fm wide, in the center of mass of the system.

π^-'s due to the enhanced production of the Δ^- resonances: now the $nn \rightarrow p\Delta^-$ process is favored (with respect to $pp \rightarrow n\Delta^{++}$) since more effectively a neutron is converted into a proton. Such interplay between the two mechanisms cannot be fully included in a non-relativistic dynamics, in particular in calculations where the baryon symmetry potential is treated classically [18, 19].

We have to note that in a previous study of kaon production in excited nuclear matter the dependence of the K^0/K^+ yield ratio on the effective isovector interaction appears much larger (see Fig.8 of ref.[9]). The point is that in the non-equilibrium case of a heavy ion collision the asymmetry of the source where kaons are produced is in fact reduced by the $n \rightarrow p$ "transformation", due to the favored $nn \rightarrow p\Delta^-$ processes. This effect is almost absent at equilibrium due to the inverse transitions, see Fig.3 of ref.[9]. Moreover in infinite nuclear matter even the fast neutron emission is not present. This result clearly shows that chemical equilibrium models can lead to uncorrect results when used for transient states of an *open* system.

5. Testing Deconfinement at High Isospin Density

The hadronic matter is expected to undergo a phase transition into a deconfined phase of quarks and gluons at large densities and/or high temperatures. On very general grounds, the transition's critical densities are expected to depend on the isospin of the system, but no experimental tests of this dependence have been performed so far. Moreover, up to now, data on the phase transition have been extracted from ultrarelativistic collisions, when large temperatures but low baryon densities are reached. In order to check the possibility of observing some precursor signals of some new physics even in collisions of stable nuclei at intermediate energies we have performed some event simulations for the collision of very heavy, neutron-rich, elements. We have chosen the reaction $^{238}U +^{238} U$ (average proton fraction $Z/A = 0.39$) at 1 $AGeV$ and semicentral impact parameter $b = 7 \, fm$ just to increase the neutron excess in the interacting region.

In Fig. 3 we report the evolution of momentum distribution and baryon density in a space cell located in the c.m. of the system. We see that after about 10 fm/c a nice

local equilibration is achieved. We have a unique Fermi distribution and from a simple fit we can evaluate the local temperature. We note that a rather exotic nuclear matter is formed in a transient time of the order of 10 fm/c, with baryon density around $3 - 4\rho_0$, temperature $50 - 60\ MeV$, energy density $500\ MeV\ fm^{-3}$ and proton fraction between 0.35 and 0.40, likely inside the estimated mixed phase region, see the following..

Here we study the isospin dependence of the transition densities [20] in a systematic way, exploring also the possibility of forming a mixed-phase of quarks and hadrons in experiments at energies of the order of a few GeV per nucleon. Concerning the hadronic phase, we use the relativistic non-linear model of Glendenning-Moszkowski (in particular the "soft" $GM3$ choice) [21], where the isovector part is treated just with ρ meson coupling, and the iso-stiffer $NL\rho\delta$ interaction [22]. For the quark phase we consider the MIT bag model [23] with various bag pressure constants. In particular we are interested in those parameter sets which would allow the existence of quark stars [24, 25], i.e. parameters sets for which the so-called Witten-Bodmer hypothesis is satisfied [26, 27]. One of the aim of our work it to show that if quark stars are indeed possible, it is then very likely to find signals of the formation of a mixed quark-hadron phase in intermediate-energy heavy-ion experiments [22].

The structure of the mixed phase is obtained by imposing the Gibbs conditions [30, 31] for chemical potentials and pressure and by requiring the conservation of the total baryon and isospin densities

$$\mu_B^{(H)} = \mu_B^{(Q)}\,,\quad \mu_3^{(H)} = \mu_3^{(Q)}\,,\quad P^{(H)}(T,\mu_{B,3}^{(H)}) = P^{(Q)}(T,\mu_{B,3}^{(Q)})\,,$$
$$\rho_B = (1-\chi)\rho_B^H + \chi\rho_B^Q\,,\quad \rho_3 = (1-\chi)\rho_3^H + \chi\rho_3^Q\,, \tag{4}$$

where χ is the fraction of quark matter in the mixed phase. In this way we get the *binodal* surface which gives the phase coexistence region in the (T,ρ_B,ρ_3) space [31, 20]. For a fixed value of the conserved charge ρ_3 we will study the boundaries of the mixed phase region in the (T,ρ_B) plane. In the hadronic phase the charge chemical potential is given by $\mu_3 = 2E_{sym}(\rho_B)\frac{\rho_3}{\rho_B}$. Thus, we expect critical densities rather sensitive to the isovector channel in the hadronic EoS.

In Fig. 4 we show the crossing density ρ_{cr} separating nuclear matter from the quark-nucleon mixed phase, as a function of the proton fraction Z/A. We can see the effect of the δ-coupling towards an *earlier* crossing due to the larger symmetry repulsion at high baryon densities. In the same figure we report the paths in the $(\rho, Z/A)$ plane followed in the c.m. region during the collision of the n-rich ^{132}Sn+^{132}Sn system, at different energies. At 300 $AMeV$ we are just reaching the border of the mixed phase, and we are well inside it at 1 $AGeV$. Statistical fluctuations could help in reducing the density at which drops of quark matter form. The reason is that a small bubble can be energetically favored if it contains quarks whose Z/A ratio is *smaller* than the average value of the surrounding region. This is again due to the strong Z/A dependence of the free energy, which favors clusters having a small electric charge. Moreover, since fluctuations favor the formation of bubbles having a smaller Z/A, neutron emission from the central collision area should be suppressed, which could give origin to specific signatures of the mechanism described in this paper. This corresponds to a *neutron trapping* effect, supported also by a symmetry energy difference in the two phases. In fact while in the hadron phase we have a large neutron potential repulsion (in particular in the $NL\rho\delta$ case), in the quark phase
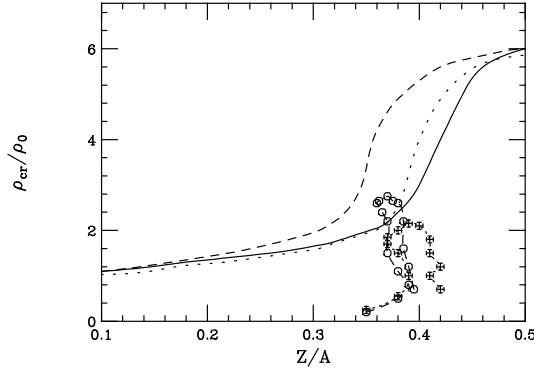
Figure 4. Variation of the transition density with proton fraction for various hadronic *EoS* parameterizations. Dotted line: $GM3$ parametrization; dashed line: $NL\rho$ parametrization; solid line: $NL\rho\delta$ parametrization. For the quark *EoS*, the MIT bag model with $B^{1/4}$=150 MeV. The points represent the path followed in the interaction zone during a semi-central ^{132}Sn+^{132}Sn collision at 1 $AGeV$ (circles) and at 300 $AMeV$ (crosses).

we only have the much smaller kinetic contribution. If in a pure hadronic phase neutrons are quickly emitted or "transformed" in protons by inelastic collisions, when the mixed phase starts forming, neutrons are kept in the interacting system up to the subsequent hadronization in the expansion stage [22]. Observables related to such neutron "trapping" could be an inversion in the trend of the formation of neutron rich fragments and/or of the π^-/π^+, K^0/K^+ yield ratios for reaction products coming from high density regions, i.e. with large transverse momenta. In general we would expect a modification of the rapidity distribution of the emitted "isospin", with an enhancement at mid-rapidity joint to large event by event fluctuations..

6. Perspectives

We have shown that collisions of n-rich heavy ions at intermediate energies can bring new information on the isovector part of the in-medium interaction at high baryon densities, qualitatively different from equilibrium *EoS* properties. We have presented quantitative results for differential collective flows and yields of charged pion and kaon ratios. Important non-equilibrium effects for particle production are stressed. Finally our study supports the possibility of observing precursor signals of the phase transition to a mixed hadron-quark matter at high baryon density in the collision, central or semi-central, of neutron-rich heavy ions in the energy range of a few *GeV* per nucleon. As signatures we suggest to look at observables particularly sensitive to the expected different isospin content of the two phases, which leads to a neutron trapping in the quark clusters. The isospin structure of hadrons produced at high transverse momentum should be a good indicator of the effect.

In conclusion the results presented here appear very promising for the possibility of extracting information from terrestrial laboratories on the Lorentz structure of the isovector nuclear interaction in a medium at densities of astrophysical interest. The use of radioactive beams at relativistic energies would be extremely important.

hadron-quark phase transition at high baryon and isospin density.

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